UCRL-PROC-217429

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Indirect Methods for Nuclear Reaction Data

J.E. Escher, F.S. Dietrich

November 30, 2005

Perspectives on Nuclear Data in the Next Decade
Bruyere-le-Chatel, France
September 26, 2005 through September 28, 2005

Indirect Methods for Nuclear Reaction Data

Jutta E. Escher and Frank S. Dietrich
Lawrence Livermore National Laboratory
P.O. Box 808, L-414, Livermore, CA 94551, USA

Abstract

Several indirect approaches for obtaining reaction cross sections are briefly reviewed. The Surrogate Nuclear Reactions method, which aims at determining cross sections for compound-nuclear reactions, is discussed in some detail. The validity of the Weisskopf-Ewing approximation in the Surrogate approach is studied for the example of neutron-induced fission of an actinide nucleus.

1 Introduction

Nuclear reaction data play an important role in nuclear physics applications. Cross sections for reactions of neutrons and light, charged particles with target nuclei across the isotopic chart, taking place at energies from several keV to tens of MeV, are required for nuclear astrophysics and other applications. Unfortunately, for a large number of reactions the relevant data cannot be directly measured in the laboratory or easily determined by calculations.

Direct measurements may encounter a variety of difficulties: The energy regime relevant for a particular application is often inaccessible – cross sections for charged-particle reactions, e.g., become vanishingly small as the relative energy of the colliding nuclei decreases. For astrophysical purposes, such as descriptions of stellar environments and evolution, reaction rates at energies below 100 keV are needed. Furthermore, many important reactions involve unstable nuclei which are too difficult to produce with currently available techniques, too short-lived to serve as targets in present-day set-ups, or highly radioactive. Producing all relevant isotopes will remain challenging even for radioactive beam facilities. In addition, electron screening affects nuclear reaction rates in laboratory experiments as well as in astrophysical environments. To date the relevant processes are not fully understood.

Cross section calculations are highly nontrivial since they often require a thorough understanding of both direct and statistical reaction mechanisms (as well as their interplay) and a detailed knowledge of the nuclear structure involved. Nuclear-structure models can provide only limited information and very little is known about important quantities such as optical-model potentials or spectroscopic factors for nuclei outside the valley of stability.

In order to overcome these limitations, several innovative indirect methods have been proposed in recent years, all of which rely on a combination of theory and experiment for success. This contribution will give a brief outline of four indirect methods for the determination of reaction cross sections: the *ANC (Asymptotic Normalization Coefficient) method*, *Coulomb Dissociation*, the *Trojan-Horse method*, and the *Surrogate Nuclear Reaction technique*. The primary focus here will be on the Surrogate method, which aims at determining reaction cross sections for compound-nuclear reactions.

2 Some indirect approaches to nuclear reactions

2.1 The Asymptotic Normalization Constant (ANC) method

The ANC method has been explored for low-energy radiative-capture reactions which are dominated by processes occuring far outside the nuclear volume [1]. The cross section for the desired reaction, $A(a,\gamma)B$, is determined by the integral $\mathcal{I} = \int dr I^B_{Aa}(r)\hat{O}(r)\phi^{scatt}(r)$, where $\phi^{scatt}(r)$ is the scattering function associated with the $a+A$ channel, $\hat{O}(r)$ is the relevant transition operator (usually of E1, E2, or M1 type), and $I^B_{Aa}(r)$ is the radial function corresponding to the projection of the state B onto the channel $a+A$. For small r values, this overlap depends on the details of the many-body wave functions involved, while its shape is well-known outside the nuclear volume: $I^B_{Aa}(r) \to C^B_{Aa}W(r)/r$, where $W(r)$ is a Whittaker function and C^B_{Aa} is the so-called asymptotic normalization constant, or ANC. For reactions that occur predominantly outside the nucleus, the short-range behavior of $I^B_{Aa}(r)$ does not need to be known. The cross section can be calculated once the ANC C^B_{Aa} is determined. This can be accomplished by measuring the cross section for a peripheral transfer reaction $A(d,b)B$, with $d = a + b$ and $B = a + A$, that involves the same asymptotic overlap norm C^B_{Aa}, as well as a known ANC C^D_{ab}.

Ideally, several different reactions are measured to reliably determine the desired ANC and thus the desired cross section. The ANC method has been used to determine, e.g., the cross sections for ^{16}O(p,γ)^{17}F via ^{16}O(^{3}He,d)^{17}F [2], ^{7}Be(p,γ)^{8}B via ^{10}B(^{7}Be,^{8}B)^{9}Be and ^{14}N(^{7}Be,^{8}B)^{13}C [3]. Applications of the ANC method are restricted to low-energy radiative capture reactions and the measured transfer reactions have to be peripheral. The associated transfer reaction calculations require optical-model potentials, the availability and reliability of which limits the number of reactions that can be considered and the accuracy to which the desired cross sections can be determined [4]. Major advantages of the approach include the large cross sections that are obtained in the transfer measurements, the small equivalent capture energies that can be reached, and the fact that the method can be used (in inverse kinematics) to determine cross sections for capture on unstable nuclei. Moreover, it has been shown recently that an approximate relationship between ANCs of mirror reactions can be employed to predict a cross section by measuring the ANC of the associated mirror reaction [5].

2.2 Coulomb Dissociation

Coulomb dissociation has been used to extract cross sections for radiative-capture reactions, $A(a,\gamma)B$, by studying the time-reversed breakup reaction in which the Coulomb field of a highly-charged target provides a virtual photon that is absorbed by the projectile, B. Due to the high flux of virtual photons provided by the target nucleus, the cross section of the breakup, $X(B,Aa)X$, is much larger than the capture cross section and can be related to the latter via the principle of detailed balance [6]. Coulomb dissociation is a simple and powerful reaction mechanism. Since the electromagnetic interaction is well known, valuable nuclear structure and reaction information can be obtained from experiments in which nuclear effects are excluded. The suppression of nuclear effects can be accomplished by selecting bombarding energies below the Coulomb barrier or, if higher energies are desired, by observing the breakup products at small forward scattering angles which (classically) correspond to large impact parameters. Coulomb dissociation has been employed, e.g., to determine the ^{7}Be(p,γ)^{8}B and ^{13}N(p,γ)^{14}O cross sections from the breakup of ^{8}B [7] and ^{14}O [8], respectively.

Applications of the Coulomb dissociation method are restricted to providing radiative capture reaction cross sections on a nucleus in its ground state. Furthermore, the relative strength of the electromagnetic multipoles are different in the radiative capture and the breakup processes; low-energy capture proceeds predominantly by E1 transitions, while higher-order contributions can play a significant role in the dissociation. Since the principle of detailed balance applies separately for each electromagnetic multipole order, additional measurements or calculations are required to extract the relevant multipole order. Additional complications, such nuclear contributions to the breakup and final-state effects, which can often be minimized by selecting a particular experimental set-up, require further studies.

2.3 The Trojan-Horse method

The Trojan-Horse method [9] provides a mechanism for circumventing the Coulomb suppression in low-energy charged-particle reactions, $x + A \rightarrow c + C$, by selecting a reaction $p + A \rightarrow s + c + C$ with a composite projectile consisting of the desired projectile and an additional fragment, $p = x + s$. The kinematic conditions are chosen such that the fragment s can be considered a spectator to the reaction between x and A. Employing a DWBA approximation in the description of the Trojan-Horse reaction and replacing the scattering wave function for the $c + C$ system by its asymptotic form for radii larger than a suitably chosen cutoff radius R_c and by zero for $r < R_c$ ("surface approximation") makes it possible to relate the measured three-body cross section to the desired two-body cross section. The method allows one to achieve very small relative kinetic energies between the "desired" projectile x and the target A – the three-body (Trojan-Horse) cross section remains finite even for vanishingly small relative energies between x and A. Not only does the Trojan-Horse approach avoid the problem of Coulomb suppression that is present in low-energy charged-particle reactions, it can also be expected that electron screening effects are negligible in this approach. This makes it, in principle, possible to obtain information on the screening effects by comparing the desired cross section extracted from a Trojan-Horse experiment to a directly measured cross section; the difference between the cross sections are attributed to screening effects [10].

The exact relationship between the measured three-body and desired two-body cross sections is complicated and requires several approximations. In typical applications of the method, only the energy dependence of the cross section is obtained and the overall scale is normalized to direct-measurement data at higher energies [9]. For testing purposes it is useful to determine a particular desired cross section with the help of several different Trojan-Horse measurements. Since Trojan-Horse experiments can be carried out in inverse kinematics, it is also possible to study reactions involving unstable targets.

The Trojan-Horse method can be applied to a variety of nuclear reactions; unlike the ANC method or Coulomb dissociation, it is not limited to radiative-capture reactions. For example, the astrophysically relevant cross section for ^{7}Li(p,α)α has been extracted from a measurement of ^{2}H(^{7}Li,$\alpha\alpha'$)n [10], the ^{3}He(d,p)^{4}He cross section was obtained from a ^{6}Li(^{3}He,pα)^{4}He experiment [11], and the ^{11}B(p,α)^{8}Be reaction was studied via ^{2}H(^{11}B,^{8}Bα)n [12]. The Trojan-Horse method was also applied to determine the low-energy nuclear scattering cross section ^{12}C$(\alpha,\alpha)^{12}$C from the ^{6}Li(^{12}C,^{12}Cα)d reaction [13].

3 The Surrogate Nuclear Reactions approach

3.1 The full Surrogate treatment

The Surrogate nuclear reaction technique is an indirect method for determining the cross section for reactions $a + A \rightarrow B^* \rightarrow c + C$ that proceed through a compound nucleus (B^*), a highly excited configuration in statistical equilibrium (see Figure 1). Formation and decay of a compound nucleus (CN) are, by definition, independent of each other (for each angular momentum and parity value) and the cross section for the "desired" reaction can be expressed as

$$\sigma_{\alpha\chi}(E_a) \quad = \quad \sum_{J,\pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi) \;\; G_{\chi}^{CN}(E_{ex}, J, \pi) \; . \tag{1}$$

Here α denotes the entrance channel $a+A$ and χ represents the relevant exit channel $c+C$. The excitation energy of the compound nucleus, E_{ex}, is related to the projectile energy E_a via the energy needed for separating a from B: $E_a = E_{ex} - S_a(B)$. The formation cross section $\sigma_{\alpha}^{CN} = \sigma(a+A \rightarrow B^*)$ can usually be calculated reasonably well by using optical potentials, while the theoretical decay probabilities G_{χ}^{CN} for the different channels χ are often quite uncertain. The objective of the Surrogate method is to determine or constrain these decay probabilities experimentally.

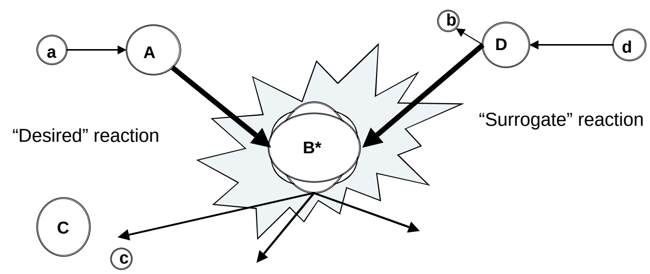

Figure 1: Surrogate reaction mechanism. The first step of the desired reaction is replaced by an alternative ("Surrogate") reaction that populates the same compound nucleus. The subsequent decay of the compound nucleus into the relevant channel is measured and used to extract the desired cross section.

In a Surrogate experiment, the compound nucleus B^* is produced via an alternative ("Surrogate"), direct reaction $d + D \rightarrow b + B^*$ and the decay of B^* is observed in coincidence with the outgoing particle b. The probability for forming B^* in the Surrogate reaction (with energy E_{ex}, angular momentum J, and parity π) is $F_{\delta}^{CN}(E_{ex}, J, \pi)$, where δ denotes the entrance channel $d+D$. The quantity

$$P_{\delta\chi}(E_{ex}) = \sum_{J,\pi} F_{\delta}^{CN}(E_{ex}, J, \pi) \;\; G_{\chi}^{CN}(E_{ex}, J, \pi) \; , \tag{2}$$

which gives the probability that the compound nucleus B^* was formed with energy E_{ex} and decayed into channel χ, can be obtained experimentally. The direct-reaction probabilities $F_{\delta}^{CN}(E_{ex}, J, \pi)$ have to be determined theoretically, so that the branching ratios $G_{\chi}^{CN}(E_{ex}, J, \pi)$ can be extracted from the measurements. In practice, the decay of the compound nucleus is modeled and the $G_{\chi}^{CN}(E_{ex}, J, \pi)$ are obtained by fitting the calculations to reproduce the measured decay probabilities and subsequently inserted in Eq. (1) to yield the desired cross section.

A full treatment of a Surrogate experiment is challenging: It involves taking into account differences in the angular momentum J and parity π distributions between the compound nuclei produced in the desired and Surrogate reactions, as well as their effect on the decay of the compound nucleus. Predicting the J^{π} distribution resulting from a Surrogate reaction is a nontrivial task since a proper treatment of direct reactions leading to highly excited states in the intermediate nucleus B involves a description of particle transfers, and inelastic scattering, to unbound states. Modeling the compound-nuclear decay requires a proper description of structural properties of the reaction products (level densities, branching ratios, internal conversion rates), plus a fission model for cases which involve that decay mode. Furthermore, applications of the Surrogate technique outside the valley of stability will require microscopic approaches to optical models and level-density prescriptions which can be extrapolated to the region of interest. The experimental determination of the probabilities $P_{\delta\chi}(E)$ requires the number of $\delta-\chi$ coincidences between the outgoing particle b and the relevant reaction channel $\chi = c + C$, as well as the total number of Surrogate reaction events (i.e. events which produce B^* in the Surrogate reaction). This, in turn, implies that the effects of target contaminants need to be minimized and that the decay channel χ can be clearly identified (e.g., from fission fragments or characteristic gamma rays). Since the Surrogate approach assumes that formation and decay of the intermediate nuclear state are independent of each other (apart from conserving constants of motion), it becomes important to estimate the probability that an equilibrated intermediate (i.e. compound) nucleus is actually formed in a particular reaction. The Surrogate method needs to be carefully tested; cross sections extracted from Surrogate benchmark experiments need to be compared to direct measurements and to results from other Surrogate experiments which aim at determining the same "desired" reaction.

The Surrogate method is very general and can in principle be employed to determine cross sections for all types of compound-nucleus reactions on a large variety of nuclei; its greatest potential value lies in applications to reactions on unstable isotopes. To date, most applications have focused on determining cross sections for neutron-induced fission for various actinides [15, 16, 17]. Early applications used (t,pf), (^{3}He,d), and (^{3}He,t) Surrogate reactions to determine (n,f) cross sections for Th, Pa, U, Pu, Np, Pu, Am, Cm, Bk, and Es [15]. More recently, Petit *et al.* studied (^{3}He,x)^{232}Th, with x = p, d, t, α, and obtained fission cross sections for ^{230}Th, ^{231}Pa, and ^{233}Pa [16]. With few exceptions [17], the majority of theses studies makes use of the Weisskopf-Ewing approximation to the full Surrogate approach. This approximation is considered in the next subsection.

3.2 The Weisskopf-Ewing approximation

The Hauser-Feshbach expression for the desired cross sections, Eq.1, conserves total angular momentum J and parity π. Under certain conditions the branching ratios $G_{\chi}^{CN}(E_{ex}, J, \pi)$ can be treated as independent of J and π and the cross section simplifies to

$$\sigma_{\alpha\chi}^{WE}(E_a) \quad = \quad \sigma_{\alpha}^{CN}(E_{ex})\, \mathcal{G}_{\chi}^{CN}(E_{ex}) \tag{3}$$

where $\sigma_{\alpha}^{CN}(E_{ex}) = \sum_{J\Pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi)$ is the reaction cross section describing the formation of the compound nucleus at energy E_{ex} and $\mathcal{G}_{\chi}^{CN}(E_{ex})$ denotes the $J\pi$-independent branching ratio for the exit channel χ. This is the Weisskopf-Ewing limit of the Hauser-Feshbach theory [14]. It provides a simple and powerful approximate way of calculating cross sections for compound-nucleus reactions. In the context of Surrogate reactions, it greatly simplifies the application of the method: It becomes straightforward to obtain the $J\pi$-independent branching ratios $\mathcal{G}_{\chi}^{CN}(E_{ex})$ from measurements of $P_{\delta\chi}(E_{ex})$ [$= \mathcal{G}_{\chi}^{CN}(E_{ex})$, since $\sum_{J\Pi} F_{\delta}^{CN}(E_{ex}, J, \pi) = 1$] and to calculate the desired reaction cross section. Calculating the direct-reaction probabilities $F_{\delta}^{CN}(E_{ex}, J, \pi)$ and modeling the decay of the compound nucleus are no longer required.

Most applications of the Surrogate method so far have been based on the assumption that the Weisskopf-Ewing limit is valid for the cases of interest. Here we present a test of this assumption for the ^{235}U(n,f) reaction. While the branching ratios $G_{\chi=fission}^{CN}(E_{ex}, J, \pi)$ cannot be directly measured in a fission experiment, they can be extracted from a calculation of the (n,f) cross section and their $J\pi$-dependence can be studied. To this end, we simulated a nuclear reaction. We extracted the branching ratios from a full Hauser-Feshbach calculation of the ^{235}U(n,f) reaction that was calibrated to an evaluation of experimental data. The model used a deformed optical potential and the level schemes, level densities, gamma strength functions, fission-model parameters, and pre-equilibrium parameters were adjusted to reproduce the available data on n-induced fission for energies from E_n= 0 to 20 MeV. The result of the fit is shown in Figure 2a. We took the extracted $G^{CN}_{fission}(E_{ex}, J, \pi)$ values to represent the "true" branching ratios. Figure 2b gives the results for the ^{235}U(n,f) reaction for fission proceeding through positive parity states in the compound nucleus ^{236}U. We observe that the branching ratios exhibit a significant $J\pi$ dependence. In particular, for low neutron energies, $E_n = 0 - 5$ MeV ($E_n = E_{ex}(^{236}U) - S_n(^{236}U)$, where S_n is the neutron separation energy in ^{236}U), the $G^{CN}_{fission}(E_{ex}, J, \pi)$ differ in both their energy dependence and their magnitude for different $J\pi$ values. With increasing energy, the differences decrease, although the discrepancies become more pronounced near the thresholds for second-chance and third-chance fission. The branching ratios for negative parity states (not shown) are very similar. It is clear that for low energies (below 3 MeV) the Weisskopf-Ewing approach is not a good approximation, while the energy regime above 5 MeV merits further study.

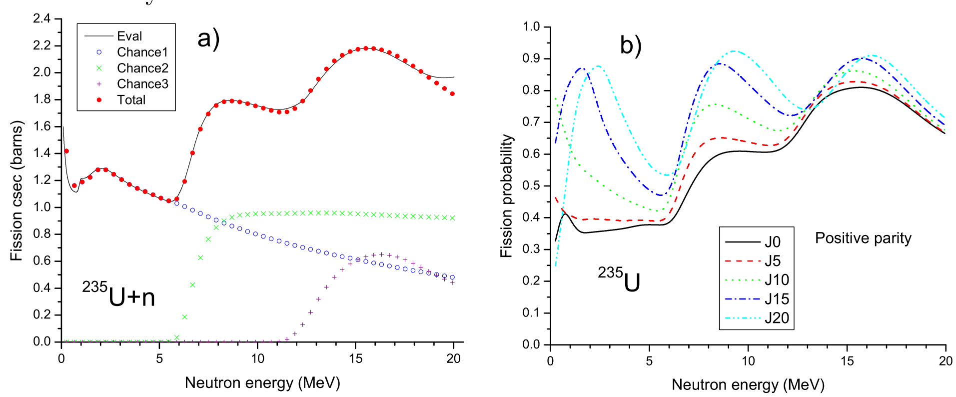

Figure 2: a) Calculated ^{235}U(n,f) cross section, calibrated to experimental data ("Eval"). Shown are the contribution to the total fission cross section from 1st, 2nd, and 3rd chance fission. b) Calculated branching ratios $G^{CN}_{fission}(E_{ex}, J, \pi)$ for fission of ^{236}U. Results are shown for $J^\pi = 0^+, 5^+, 10^+, 15^+, 20^+$.

These results illustrate an important point: It is not *a priori* clear whether the Weisskopf-Ewing limit applies to a particular reaction in a given energy regime. E.g., restricting one's consideration to reactions induced by neutrons with kinetic energies above several MeV does not guarantee the validity of the Weisskopf-Ewing limit. If the states that are populated in the compound nucleus before the decay have large angular momenta, the condition $J \lesssim \sigma_{\text{cutoff}}$ required for the Weisskopf-Ewing limit to be a good approximation to Hauser-Feshbach [14] is no longer satisfied and the branching ratios may depend on $J\pi$. Furthermore, the Weisskopf-Ewing assumption breaks down near the threshold for second-chance and, to a lesser degree, third-chance fission.

The quantity $P_{\delta\chi}(E)$, which is measured in a Surrogate experiment, can be calculated in our simulation: $P_{\delta,fission}(E_{ex}) = \sum_{J,\pi} F^{CN}_\delta(E_{ex}, J, \pi)\, G^{CN}_{fission}(E_{ex}, J, \pi)$, where the $\mathcal{G}^{CN}_{fission}$ are the extracted fission branching ratios and $F^{CN}_\delta(E_{ex}, J, \pi)$ denotes the probability for populating compound nuclear states in the relevant Surrogate reaction. For the purpose of a sensitivity study, we chose the three probability distributions shown in Figure 3a. Calculating the desired fission cross section via the formula $\sigma^{WE}_{(n,f)}(E_{ex}) = \sigma^{CN}_{n+target}(E_{ex})\, \mathcal{G}^{CN}_{fission}(E_{ex})$ then corresponds to a Surrogate analysis in the Weisskopf-Ewing approximation. The compound-nucleus formation cross section $\sigma^{CN}_{n+target}(E_{ex})$ was taken to be the one that was used for the fit shown in Figure 2a.

Results for the ^{235}U(n,f) cross section obtained from the simulated Surrogate experiment are compared to each other and to the "reference" cross section in Figure 3. We observe that the inferred cross sections are too large, by about 40% for energies above 5 MeV and up to a factor of three for smaller energies. The influence of the spin-parity distribution in the compound nucleus on the extracted cross sections is significant; again, this reflects the fact that the Weisskopf-Ewing approximation is deficient at low energies (below about 3 MeV) when not enough channels are open and at higher energies when the spin-parity distribution extends to values significantly higher than the spin-cutoff parameter in the level densities in the decay channels.

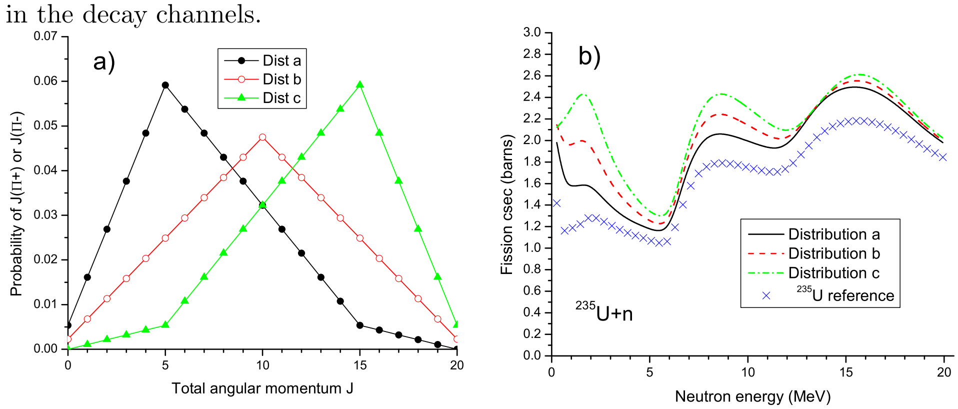

Figure 3: a) Distributions of total angular momentum for the compound nucleus considered. The mean angular momentum is $\langle J \rangle = 7.03$, 10.0, and 12.97 for distributions a, b, and c, respectively; positive and negative parities are taken to be equally probable. The distributions were chosen solely to perform a sensitivity study. b) Weisskopf-Ewing estimates of the ^{235}U(n,f) cross section, using the distribution of angular momenta shown in Figure 3a. The crosses represent the "reference" ^{235}U(n,f) cross section from the fit.

Some recent Surrogate experiments [18] have employed a "Surrogate Ratio" approach: the experiments measured the ratio $R = \sigma_{\alpha_1,\chi_1}/\sigma_{\alpha_2,\chi_2}$ of the cross sections of two compound-nuclear reactions, $a_i + A_i \rightarrow B_i^* \rightarrow c_i + C_i$ $(i = 1, 2)$, using the Surrogate method under the assumption that the Weisskopf-Ewing approximation is valid. An independent determination of the cross section σ_{α_2,χ_2} was then used to deduce σ_{α_1,χ_1}. A simulation analogous to the one employed above indicates that this method has some advantages (and might lead to some improvements) over simply using the Weisskopf-Ewing approximation in the manner discussed above [19].

4 Summary

We have briefly reviewed several indirect approaches that have recently been employed to obtain cross sections for reactions that are difficult to measure directly. The primary focus of the discussion has been on the Surrogate Nuclear Reaction method. The sample calculations presented here indicate that further work is required to move from earlier, approximate implementations of the method to a more complete treatment. Both theoretical work and benchmark experiments are needed in order to assess the range of its applicability.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory (LLNL) under contract No. W-7405-Eng-48. Partial funding was provided by the Laboratory Directed Research and Development Program at LLNL under project 04-ERD-057.

References

[1] A.M. Mukhamedzhanov, C.A. Gagliardi, and R.E. Tribble, Phys. Rev. C **63**, 024612 (2001); A.M. Mukhamedzhanov, R.E. Tribble, and N.K. Timofeyuk, *ibid.* **51**, 3472 (1995); H. M. Xu *et al.*, Phys. Rev. Lett. **73**, 2027 (1994).

[2] C. A. Gagliardi *et al.*, Phys. Rev. C **59**, 1149 (1999).

[3] A. Azhari *et al.*, Phys. Rev. C **63**, 055803 (2001); *ibid.* **60**, 055803 (1999); Phys. Rev. Lett. **82**, 3960 (1999).

[4] L. Trache *et al.*, Phys. Rev. C **61**, 024612 (2000); J.C. Fernandes *et al.*, *ibid.* **59**, 2865 (1999).

[5] N.K. Timofeyuk and P. Descouvemont, Phys. Rev. C **71**, 064305 (2005); N.K. Timofeyuk and A.M. Mukhamedzhanov, *et al.*, Phys. Rev. Lett. **91**, 232501 (2003); L. Trache *et al.*, Phys. Rev. C **67**, 062801(R) (2003).

[6] G. Baur, K. Hencken, and D. Trautmann, Prog. Part. Nucl. Phys. **51**, 487 (2003), G. Baur and H. Rebel, Annu. Rev. Nucl. Part. Sci. **46**, 321 (1996); G. Baur, C. Bertulani, and H. Rebel, Nucl. Phys. **A458**, 188 (1986).

[7] F. Schümann *et al.*, Phys. Rev. Lett. **90**, 232501 (2003); B. Davids and S. Typel, Phys. Rev. C **68**, 045802 (2003); B. Davids *et al.*, Phys. Rev. Lett. **86**, 2750 (2001); Iwasa *et al.*, *ibid.* **83**, 2910 (1999); T. Kikuchi *et al.*, Eur. Phys. J. A **3**, 213 (1998); Phys. Lett. B **391**, 261 (1997).

[8] T. Motobayashi *et al.*, Phys. Lett. B **264**, 259 (1991).

[9] S. Typel and G. Baur, Ann. Phys. **305**, 228 (2003); G. Baur and S. Typel, Prog. Theor. Phys. Suppl. **154**, 333 (2004); H.H. Wolter and S. Typel, Nucl. Phys. A **722**, 215c (2003); G. Baur, Phys. Lett. B **178**, 135 (1986).

[10] C. Spittaleri *et al.*, Phys. Rev. C **60**, 055802 (2004); M. Lattuada *et al.*, Ap. J. **562**, 1076 (2001).

[11] M. La Cognata, Nucl. Phys. A **758**, 98c (2005).

[12] C. Spittaleri *et al.*, Phys. Rev. C **69**, 055806 (2004).

[13] C. Spittaleri *et al.*, Eur. Phys. J. A **7**, 181 (2000); M. Aliotta *et al.*, AIP Conf. Proc. **513**, 261 (2000).

[14] E. Gadioli and P. E. Hodgson, *Pre-Equilibrium Nuclear Reactions* (Clarendon Press, Oxford, 1992); F. S. Dietrich, Technical Report No. UCRL-TR-201718, Lawrence Livermore National Laboratory, Livermore, CA, 2004 (unpublished).

[15] J.D. Cramer and H.C. Britt, Nucl. Sci. and Eng. **41**, 177 (1970); J.D. Cramer and H.C. Britt, Phys. Rev. C **2**, 2350 (1970); B.B. Back *et al.*, *ibid.* **9**, 1924 (1974); B.B. Back *et al.*, *ibid.* **10**, 1948 (1974); H.C. Britt and J.B. Wilhelmy, Nucl. Sci. and Eng. **72**, 222 (1979).

[16] M. Petit *et al.*, Nucl. Phys. A **735**, 345 (2004); M. Aiche, this volume.

[17] W. Younes and H.C. Britt, Phys. Rev. C **67**, 024610 (2003); *ibid.* **68**, 034610 (2003).

[18] C. Plettner *et al.*, Phys. Rev. C **71**, 051602 (2005); J. Burke *et al.*, LLNL Technical Report (2005), UCRL-TR-214631.

[19] J.E. Escher and F.S. Dietrich, LLNL Report (2005), UCRL-TR-212509.